Prediction of collision events: an EEG coherence analysis

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Abstract

Objective: A common daily-life task is the interaction with moving objects for which prediction of collision events is required. To evaluate the sources of information used in this process, this EEG study required participants to judge whether two moving objects would collide with one another or not. In addition, the effect of a distractor object is evaluated.

Methods: The measurements included the behavioural decision time and accuracy, eye movement fixation times, and the neural dynamics which was determined by means of EEG coherence, expressing functional connectivity between brain areas.

Results: Collision judgment involved widespread information processing across both hemispheres. When a distractor object was present, task-related activity was increased whereas distractor activity induced modulation of local sensory processing. Also relevant were the parietial regions communicating with bilateral occipital and midline areas and a left-sided sensorimotor circuit.

Conclusions: Besides visual cues, cognitive and strategic strategies are used to establish a decision of events in time. When distracting information is introduced into the collision judgment process, it is managed at different processing levels and supported by distinct neural correlates.

Significance: These data shed light on the processing mechanisms that support judgment of collision events; an ability that implicates higher-order decision-making.

Keywords: functional connectivity; decision-making; distractor

1. Introduction

The ability to deal with collision events is a sophisticated skill that involves perceptual decision-making; a function that uses various information processing sources for guiding behaviour (Regan and Gray, 2000). Important in making an appropriate prediction regarding a potential collision is dealing with the combination of spatial and temporal information, processing that associates with distinct neural correlates (Coull and Nobre, 1998; Marshall and Fink, 2001; Schubotz and von Cramon, 2001; Coull et al., 2004). In particular, Lux et al. (2003) observed that judging spatial congruence increased activity in the right hemisphere whereas evaluating temporal synchrony activated a left hemisphere circuit. Furthermore, when attending simultaneously to spatial locations and temporal intervals, hemispheric activities preferentially implicated the right and left parietal regions, respectively (Coull and Nobre, 1998). However, when collision judgment is required, and temporal information needs to be used in conjunction with spatial information in order to extrapolate trajectory changes over time of the moving objects, increased activity in the left parietal cortex becomes dominant, underlining its involvement in perceptual spatio-temporal integration (Assmuss et al., 2003). As the left parietal cortex is also involved in skilled actions and gesture discrimination (Hanna-Pladdy et al., 2001; Hermsdorfer et al., 2001; Buxbaum et al., 2003), the premise has been made that similar neural circuitry is used for achieving perceptual and motor predictions for which events in time are established (Schubotz, 2007). This hypothesis suggests that successful decision-making requires the coupling of task-independent regions of prediction with specialized task-dependent sites. During decision-making, it is also important that distracting information from the environment is ignored or inhibited as much as possible, as distractors interfere with processing of the target task (Ruff and Driver, 2006). In order to cope with a distractor situation, visual processing helps to focus attention on the relevant task characteristics and filter out the distracting irrelevant ones (Friedman-Hill et al., 2003).

This implies that attentional control enables to modulate competition between the task relevant and irrelevant information.

To examine the process of perceptual decision-making, the present study assesses the neural and behavioural correlates as well as eye movements that are associated with a collision judgment task of moving objects. In addition, the influence of a distractor object upon the task processing demands is evaluated. For assessment of the neural dynamics and identification of higher-order decision-making processes, we use EEG methods and focus on coherence analysis, which expresses functional communication between brain areas. The hypothesis is made that the collision task would involve distributed information processing, with additional resources in the presence of a distractor. It is further hypothesized that behavioural success of decision-making as well as directed eye movements would be affected by the complexity of the collision task.

2. Methods

2.1 Subjects

Thirteen participants (seven female, age: 22.8±1.4 years) took part in the experiment. They were right-handed as determined by the Edinburgh handedness inventory (Oldfield, 1971). In accordance with the declaration of Helsinki, all gave informed consent to participate in the study, which was approved by the local ethics committee. The data from one participant was excluded from analysis due to excessive EEG artefacts.

2.2. Task and procedure

The participants were asked to perform a decision-making task that required judgment whether two orthogonally moving objects would collide with one another behind a central mask (Fig. 1). Each trial started with the presentation of a fixation cross for at least 600 ms, including a minimum of 100 ms of uninterrupted fixation. After appropriate fixation, a white and black object with a diameter of 0.4º were presented either 3.6º or 7.6º on the left, right, upper or lower side of the screen's centre. Subsequently, the objects would start to move in an orthogonal manner towards the mask (height and width of 3.6º) with a speed of 2.8 or 5.6º/s. As soon as the objects started to move, the participants needed to judge whether the white and black object would collide with one another (or not) behind the mask. This point of collision (1300 ms after onset) is, however, never shown as the mask would hide the final motions of the objects (1200 ms after onset). In half of the trials, the white and black object would collide (target hit), whereas in the other half of trials, they would not (target miss). Participants were asked to react as fast and as accurate as possible in their decision-making (yes or no) by using designated keys with their right hand. After a further 700 ms or until a response was made, a blank screen occurred that marked the inter-trial interval of 1580±375 ms. An additional performance condition was included that involved a third moving object towards the mask. The grey object moved at a similar speed (± 19%) along with the black object on the side nearest to the white object. There were eight performance blocks with 128 trials per performance condition. The performance conditions (collision without distractor, collision with distractor) and type of collision (target hit vs. target miss) were randomized within blocks. Every 20 trials, feedback was provided about the number of correct responses. A control condition (n=32 trials) that required subjects to judge whether or not a distractor was present was also included, with similar responses (yes or no) as for the experimental task. There was a short break half way through the experiment. Before the start of the experiment, a short training session was included. The behavioural measurements of the task were the decision time (ms) and decision accuracy (correct or incorrect).

Insert Fig. 1 about here

2.3. EEG recordings and analysis

An Electrical Geodesic Inc. 128-channel system recorded continuous EEG. The signal was amplified, sampled at 250 Hz, band-pass filtered (0.05-100 Hz) and vertex referenced.

Data pre-processing was carried out using BESA software (MEGIS Software GmbH, Gräfelfing, Germany) including notch-filtering at 50 Hz, controlling for artefacts such as eye movements and EMG-related activity, and application of a virtual reference-free montage. An advantage of a reference-free montage is that the measures improve the borders of synchronous regions and reduce erroneous synchronies (Lachaux et al., 1999) as standard EEG recordings depend on the locations of both recording and reference electrodes. Processing was continued using the EEGLAB Matlab Toolbox (Delorme and Makeig, 2004) with segmentation of the trials time-locked to the start of the task and into epochs comprising 700 ms of fixation time and 1600 ms of task performance. Wavelet analysis extracted coherence values across 200 data points. Baseline data were calculated by averaging the coherence scores between -150 ms and 0 ms, and subsequently subtracted from all coherence values. The resulting data were averaged into 21 time slots of 100 ms and provided 550 ms of fixation time (baseline) and 1450 ms of task performance. Data were evaluated in the beta frequency band (12-30 Hz). Based on earlier studies (Classen et al., 1998; Spapé and Serrien, 2010), we adopted a region of interest approach that made use of a number of 15 electrodes. These were considered as overlying prefrontal (F3, F4), premotor (FC3, FC4), mesial fronto-central (Fz, FCz, Cz), sensorimotor (C3, CP3, C4, CP4), parietal (P3, P4), and occipital (O1, O2) areas. Coherence was used as an estimate of functional connectivity in the frequency domain between these electrodes. As a normalized measurement of coupling between two signals at any given frequency, coherence varies between 0 (no correlation) and 1 (perfect correlation). Before statistical comparisons were made, coherence levels were transformed using the inverse hyperbolic tangent to stabilize variances. In addition, EEG power was measured in the beta band at the individual electrodes, and stabilized by logarithmic transformation. Averages were estimated for the different performance conditions.

2.4. Eye tracking recordings and analysis

Eye tracking data was obtained using the Tobii 1750 (Tobii Technology, Stockholm, Sweden), which captured gaze position at 50 Hz during the entire length of the trials. Processing of binocular gaze data was conducted using Matlab and included scanning for invalid data such as blinks, with linear interpolation to minimize the effect of artefacts. Subsequently, the data were averaged to form a single gaze position followed by segmentation into epochs, synchronized to the start of the task and of similar size as the EEG data. To analyze gaze position, one static and three dynamic hotspots were created, based on the position of the mask and the three moving objects, respectively. If the data indicated that the participant was looking within 1.0º of an object, then this was labelled as a fixation of that particular object. If the data suggested that the participant was not looking at the objects and gazed within the constraints of the mask, then this was classified as a mask fixation. The eye movement measurements were the fixation times that were attributed to both collision objects, the distractor object and the mask. The remaining time consisted of fixation elsewhere or shifting between locations/objects.

2.5. Statistical design

Behavioural and eye movements. Decision time, decision accuracy, fixation times of the moving objects, and fixation time of the mask were analyzed by means of 2 x 2 ANOVAs with factors performance condition (no distractor, with distractor) and target (target hit, target miss). The fixation time of the distractor object was analyzed by means of a t-test with factor target (target hit, target miss). All data were tested for normality by means of Shapiro-Wilk tests. As decision accuracy failed the test ($p<0.05$), the data were transformed using a logarithmic procedure.

EEG data. To establish the collision network, the first 10 time slots after task onset were used to establish significance with respect to baseline: if individual t-tests showed 3 or more time slots to be significantly different in a consistent direction, the connection was considered as being robustly affected by the experimental condition. Thus, the collision network was obtained by testing the coherence time slots against 0. A similar approach was used for defining the distractor network and contrasted the coherences from the collision tasks without vs. with distractor. To compensate for multiple comparisons, the probability of a type-1 error was reduced to 0.01.

Correlation between behavioural/eye movement data and EEG observations. Pearson correlation coefficients were calculated between the coherence scores and the behavioural measurements of decision time and accuracy. Additional correlations were calculated between the coherences of the collision network with distractor and the fixation time of the distractor as provided by the eye movement recordings.

3. Results

3.1. Behavioural data and eye movements

The behavioural data and eye movement measurements are presented in Table 1. With respect to the behavioural data, decision time revealed a significant effect due to distractor presence whereas decision accuracy was not affected. Furthermore, the eye movement measures showed that fixation times of the moving objects and mask changed significantly when the distractor was present during collision judgment. In addition, the type of collision (target hit vs. target miss) additionally influenced the fixation times of the moving objects and distractor object.

Insert Table 1 about here

3.2. EEG data

3.2.1. Collision network

Compared to baseline, a network associated with the overall demands of the collision judgment task became apparent across time and consisted of distributed functional couplings. These involved both hemispheres with a particular implication of a bilateral midline circuit

(Fig. 2). The mean coherence score of this collision network was 0.358±0.026, and the average increase in coherence during collision judgment as compared to baseline was 16%. To verify whether changes in power could have contributed to the coherence effects, correlations were calculated between the coherence scores of the network couplings and the power scores of the individual electrodes. The analyses revealed no significant correlations ($p>0.05$). This implies that although changes in power could have contributed to adjustments in coherence through non-linear effects (Florian et al., 1998), the present effects of coherence were independent of power modulations. The mean correlation score of the collision network was -0.18.

Insert Fig. 2 about here

Two additional contrasts of interest were conducted with respect to the collision network: (1) to define the neural couplings that associated with correct responses, (2) to establish the relevance of the observed left-sided sensorimotor activation and to rule out an effect of motor response preparation/execution due to the button press. First, contrasting the couplings of the correct vs. incorrect responses identified the left prefrontal-midline and right prefrontal-centroparietal couplings as the most significant links ($p<0.05$), keeping in consideration that 25% of the responses were classified as incorrect. Second, the coherences of the control task (judgment of distractor presence) were compared to those of the collision judgment task. This comparison revealed that the left sensorimotor couplings remained activated ($p<0.05$), suggesting the importance of the motor system for collision judgment.

Correlations between the behavioural and coherence measurements showed that decision time negatively correlated with left prefrontal-motor and parietal-occipital regions ($p<0.05$). This implies that faster decision times can be achieved due to intensified sensory processing or cognitively guided motor regulation. Furthermore, a positive correlation between decision time and right prefrontal-midline areas was noticed, which indicates that increased cognitive processing, likely due to supervisory control mechanisms, underlies longer decision times. Decision accuracy correlated positively with coherence of right prefrontal-centroparietal site ($p<0.05$), suggesting that increased cognitive sensorimotor processing leads to a higher degree of decision accuracy.

3.2.2. Distractor network

Compared to the collision task without distractor, a network due to the presence of the distractor became evident across time and consisted of distributed functional couplings. These included multiple links across both hemispheres with a particular involvement of an occipital circuit (Fig. 3). The mean coherence score of the distractor network was 0.422±0.031, and the average increase in coherence as a result of the distractor presence was 11%. Correlations between the coherence scores of the couplings and the power scores of the individual electrodes demonstrated no significant effects ($p>0.05$), underlining that the coherence changes were independent of the power modulations. The mean correlation score of the distractor network was -0.26.

Correlations between the behavioural and coherence measurements revealed that decision time negatively correlated with left premotor-occipital, left motor-occipital and right parietal-occipital areas ($p<0.05$). Hence, faster decision times related with higher coherence in these occipital-associated links, which suggests that an enhanced sensorimotor processing component supports the response time. For fixation time of the distractor object, a positive correlation was noted with the right parietal-midline coupling ($p<0.05$), and a negative correlation with the left parietal-midline coupling ($p<0.05$), indicating the distinct involvement of sensory processing components with respect to the distractor.

Insert Fig. 3 about here

4. Discussion

Perceptual decision-making is an essential function that integrates various sources of information in view of a behavioural response (Schall, 2003; Gold and Shadlen, 2007). Although this process enables the decision-making network to link the decision with the preparation of the response (Heekeren et al., 2008), it is hypothesized that similar neural circuitry supports the formulation of perceptual and motor predictions (Schubotz, 2007). In the present study, participants performed a decision-making task that involved judging whether two objects would collide with one another or not. The presence of a distractor object was additionally evaluated. Here, the focus was on identifying the neural dynamics of the decision-making task. To this end, we adopted two approaches: (1) to establish the functional connectivity patterns of the involved brain areas, and (2) to assess a correlation between the neural and behavioural measures.

4.1. Collision judgment: a distributed network

To determine the neural correlates of collision judgment, the task performance was compared to baseline. This comparison revealed distributed activity that involved left prefrontal-central and right prefrontal-parietal coupling. In addition, a bilateral parieto-occipital and midline-prefrontal circuit was noted. First, the involvement of the left-lateralized network can be argued to support decision-making and the formulation of the response. The left dorsolateral prefrontal cortex through links with premotor and primary motor areas appears pivotal in this process (Heekeren et al., 2006). Second, the right dorsolateral prefrontal cortex and premotor cortex connected with association areas, which reflect their position in evaluating sensory information from posterior regions (Fink et al., 1999). The significant participation of both prefrontal areas is further supported by the neural-behavioural correlation analyses which showed that decision time and accuracy strongly associated with prefrontal-associated couplings. Also, the involvement of the right premotor cortex (in addition to the left premotor cortex) in collision judgment is particularly relevant and may relate to a prediction of change (Schubotz, 2007). Third, the midline region connected with both prefrontal cortices, supporting its role within a supervisory system in guiding cognitive control mechanisms (Botvinick et al., 2001; Rushworth et al., 2004). It should, however, be noted that the midline area is also involved in internal movement selection (Deiber et al., 1991) and sequencing (Picard and Strick, 1997); processes that are also involved in the present context. Finally, bilateral parietal-occipital connectivity was observed, which underlines functional loops that integrate information exchange between sensory sites. As both parietal areas have significant roles in spatial and temporal processing (Coull and Nobre, 1998; Assmuss et al., 2003, 2005), the argument can be made that coupling with occipital areas would enable to acquire relevant sensory input.

In the context of spatio-temporal processing, it has been established that spatial information is processed preferentially in the right hemisphere (Marshall and Fink, 2001), whereas temporal information mainly activates left hemisphere pathways (Coull and Nobre, 1998). Collision judgment requires, however, an integration of spatial and temporal signals. In this respect, Assmuss et al. (2003, 2005) observed a well-defined left parietal activation during prediction of collision events of moving objects. The present study confirms the importance of the left parietal area in collision judgment, but extends earlier data by highlighting the significance of functional communication between left parietal and occipital as well as midline regions. That is, whereas the left parietal-occipital coupling supports the speed of decision-making, the left parietal-midline coupling is important in assisting the correct decisions. As the midline region also connects with various frontal areas, it is likely involved in hierarchically distinct cognitive processes, driven by decision uncertainty (Grinband et al., 2006). In addition to the left parietal region, the homologous right side was also observed to be a major component in the collision judgment process with extensive links to distributed regions. Accordingly, it can be argued that the functional properties of the parietal regions provide key signals for the spatio-temporal prediction of collision events.

The findings also revealed a strong involvement of the sensorimotor system, which extends earlier work (Field and Wann, 2005). Not only were activation links with the somatosensory association cortices noted, there was also a left-sided sensorimotor circuit that is commonly observed when preparing for a voluntary motor response. When controlling for the button press, this activation remained present, which highlights the involvement of the sensorimotor system in decision-making and in predicting event dynamics (Schubotz, 2007). However, as collision judgment is highly context-dependent, the argument can be made that the particular implication of a brain region will vary as a function of the task constraints (e.g., directing attention to the spatial locations or moving objects). Together, these results show that prediction of collision events implicates functional distinguishable couplings that contribute to particular control functions within neural networks.

4.2. Effect of distractor on collision judgment

The flanker task, which requires responses to target stimuli that are surrounded by distracting stimuli, is often used to measure effects of distraction (Eriksen and Eriksen, 1974). Distractor processing induces a delay in evaluation of the target task (Ruff and Driver, 2006). In the present study, the impact of a distractor object on collision judgment of two target objects was examined. It was argued that the distractor would influence the decision-making process due to stimulus conflict.

The results showed that the distractor object interfered with collision judgment and delayed the decision time. Neurally, the distractor network involved widespread activation across both hemispheres, which signifies that the distracting information impacted on various processing mechanisms such as inhibition of the distractor activity (Machado et al., 2007) or amplification of the target activity (Egner and Hirsch, 2005). In particular, distractor fixation time correlated with coherence from midline-parietal areas; processing thought to reflect selective cognitive sensory processing with respect to the distractor object. Conversely, task-related decision time correlated with coherence in occipital-associated links that biased sensorimotor processing in favour of the task planning. Combined, these observations denote that distinct neural circuitry copes with disturbed task demands due to distracting information.

5. Conclusion

Decision-making as required during collision judgment involves widespread information communication across both hemispheres. This underlines that besides visual cues, cognitive and strategic strategies are required to establish a decision of events in time. When distracting information is introduced into the collision judgment process, it is managed at different processing levels and supported by distinct neural correlates. Overall, these data shed light on the regulatory mechanisms that support prediction of collision events; an ability that implicates higher-order decision-making.

Table Caption

Table 1. Means and standard deviations (in parentheses) of the behavioural data (decision time, decision accuracy) and eye movement measurements (fixation times of the moving objects, fixation time of the mask, fixation time of the distractor object) associating with performance condition (collision without distractor vs. with distractor) and type of collision (target hit vs. target miss). F or t values and levels of significance are indicated with * $p<0.05$, ** $p<0.01$, ns = not significant.

Figure Caption

Fig. 1. Collision task without distractor (upper panel) and with distractor (lower panel). (a) At the start of the task, the black and white target objects move orthogonally towards the centrally positioned mask. (b) After 1200 ms these objects disappear behind the mask. In the collision task with distractor, the grey distractor object moved along with the black object on the side nearest to the white object.

Fig. 2. The collision judgment task associated with a distributed network across both hemispheres. The coding of the interregional couplings illustrates the distinct percentage increases as compared to baseline. Also illustrated are the significant correlations between the neural couplings and the behavioural measurements of decision time (DT) and decision accuracy (DA). The positive (+) and negative (-) correlations are shown.

Fig. 3. Effect of the distractor linked with a widespread network across both hemispheres. The coding of the interregional couplings illustrates the distinct percentage increases as compared to the condition with no distractor. Also shown are the significant correlations between the neural couplings and the behavioural measurements of decision time (DT) and fixation time (FT). The positive (+) and negative (-) correlations are indicated.

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Fig. 1

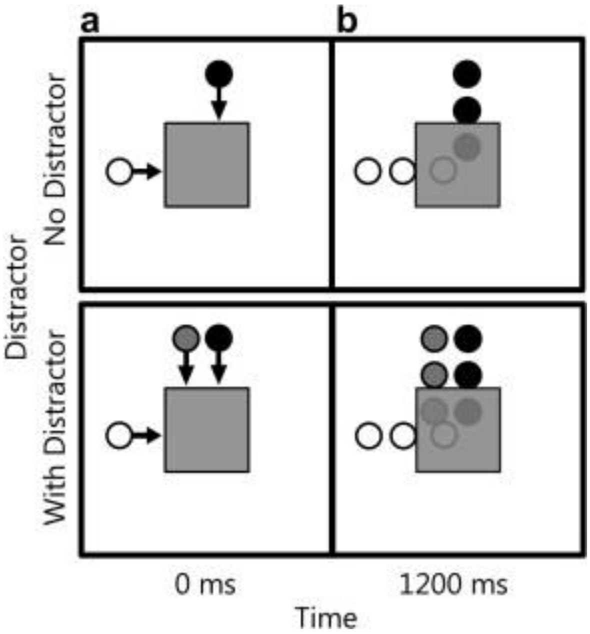

Fig. 2

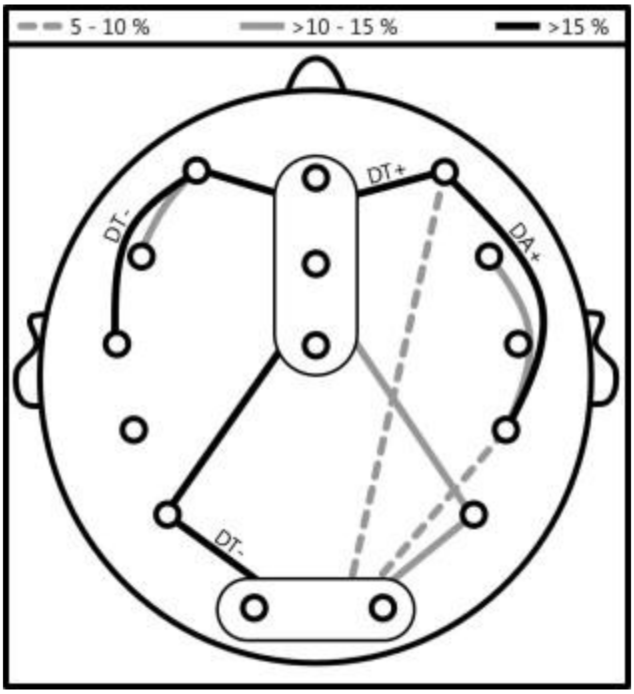

Fig. 3

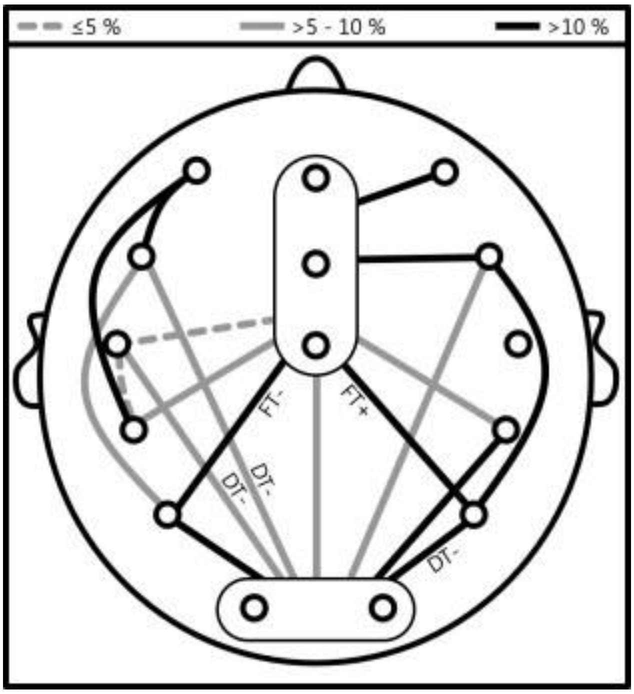

Table 1

Variable	*Distractor*		*Sign.*
	No	*With*	*F or t*
Decision time (ms)	1341 (±315)	1391 (±328)	6.46*
Decision accuracy (%)	74 (±10)	76 (±11)	ns
Fixation black object (ms)	180 (±22)	209 (±25)	14.35**
Fixation white object (ms)	238 (±33)	186 (±28)	31.19**
Fixation mask (ms)	377 (±32)	323 (±36)	4.60*

Variable	*Target*		*Sign.*
	Hit	*Miss*	*F or t*
Decision time (ms)	1372 (±318)	1360 (±321)	ns
Decision accuracy (%)	75 (±11)	75 (±12)	ns
Fixation black object (ms)	218 (±24)	170 (±29)	22.73**
Fixation white object (ms)	224 (±21)	201 (±19)	10.60**
Fixation mask (ms)	359 (±25)	331 (±18)	ns
Fixation distractor (ms)	243 (±38)	339 (±44)	-7.51**